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PATENT & TRADEMARK OFFICE

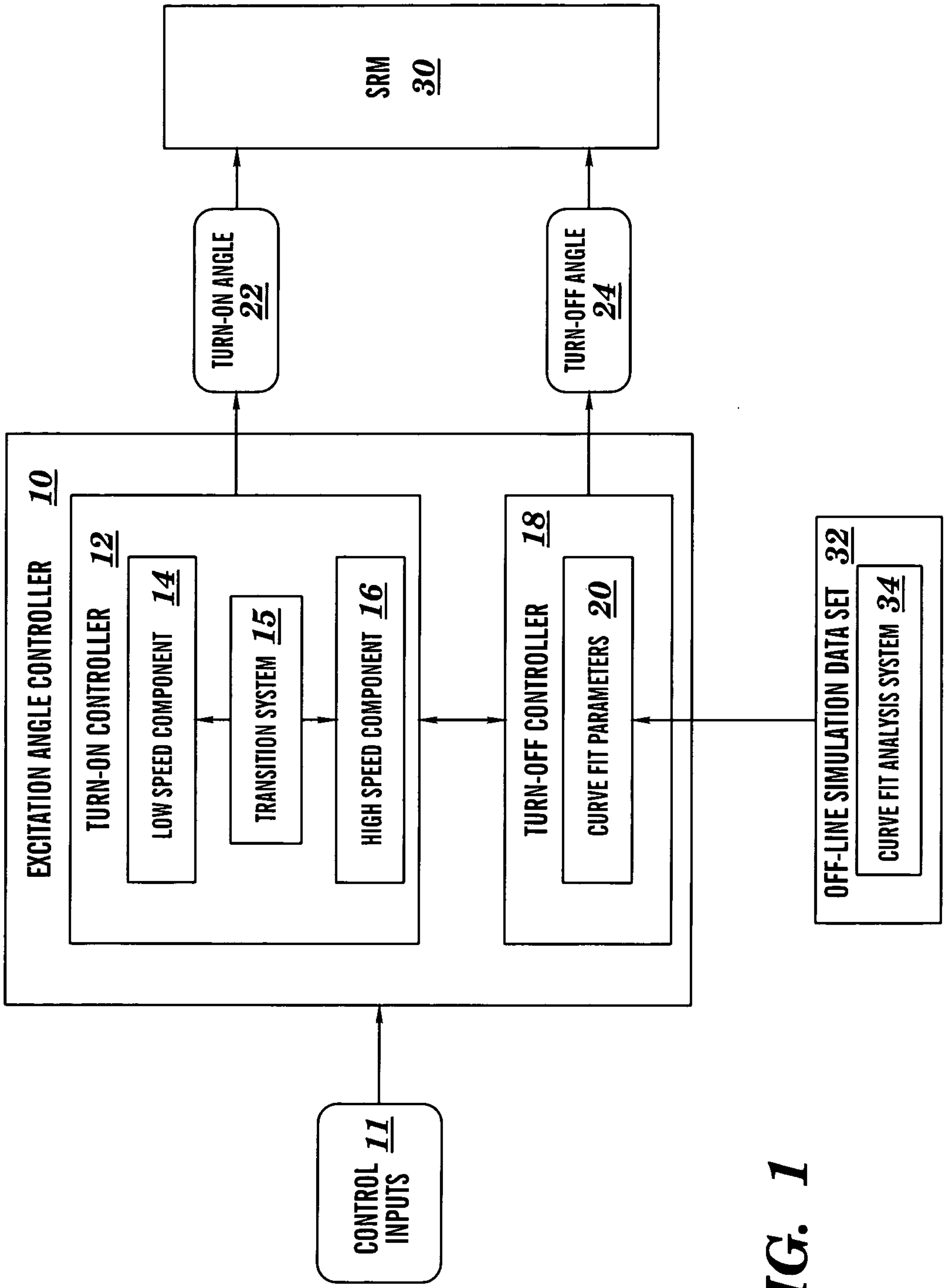

FIG. 1

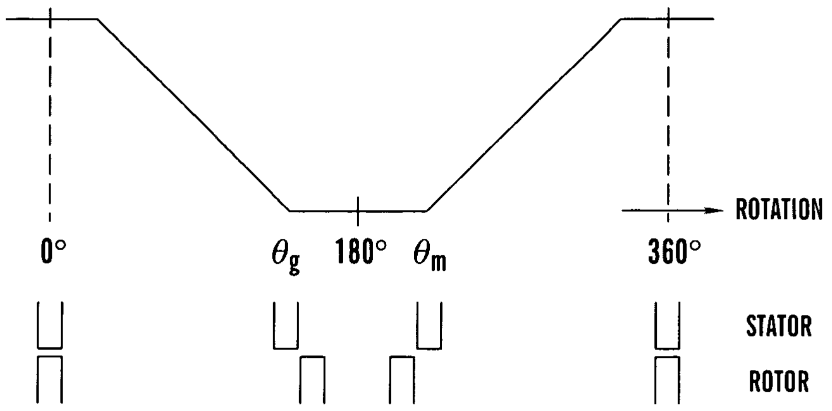
ROTATION
0°
θ_g
180°
θ_m
360°
STATOR
ROTOR

FIG. 2

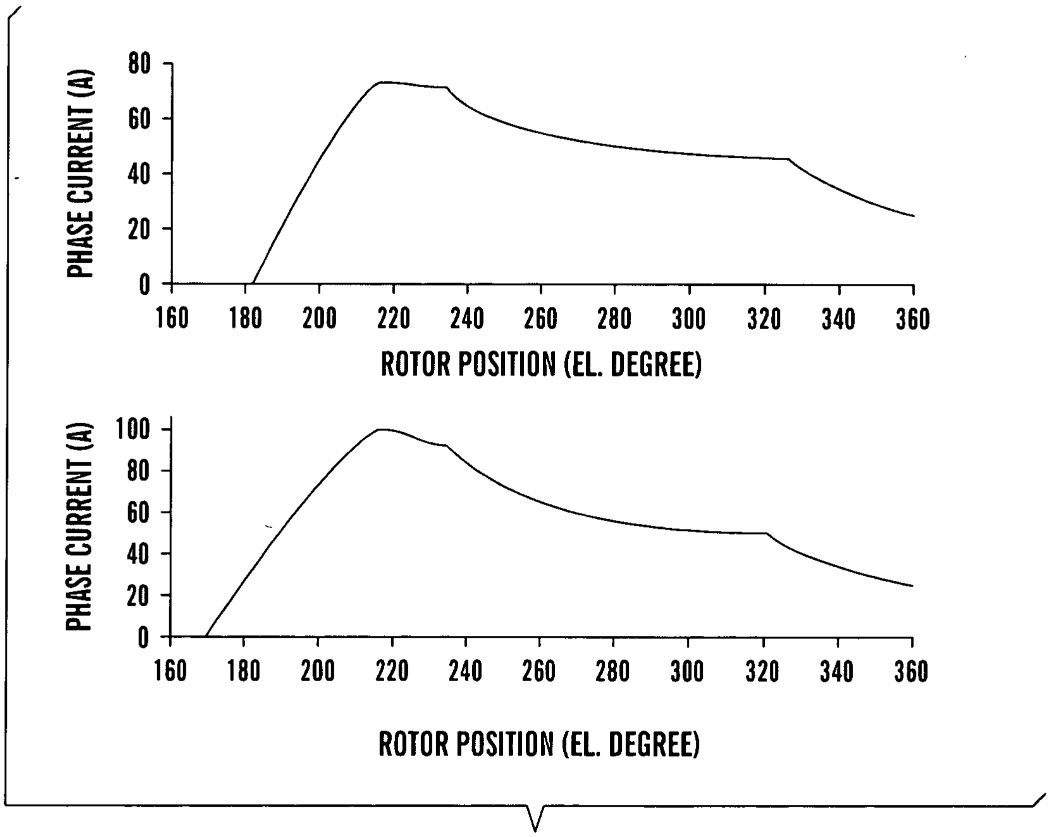
PHASE CURRENT (A)
0
20
40
60
80
160
180
200
220
240
260
280
300
320
340
360
ROTOR POSITION (EL. DEGREE)
PHASE CURRENT (A)
0
20
40
60
80
100
160
180
200
220
240
260
280
300
320
340
360
ROTOR POSITION (EL. DEGREE)

FIG. 3

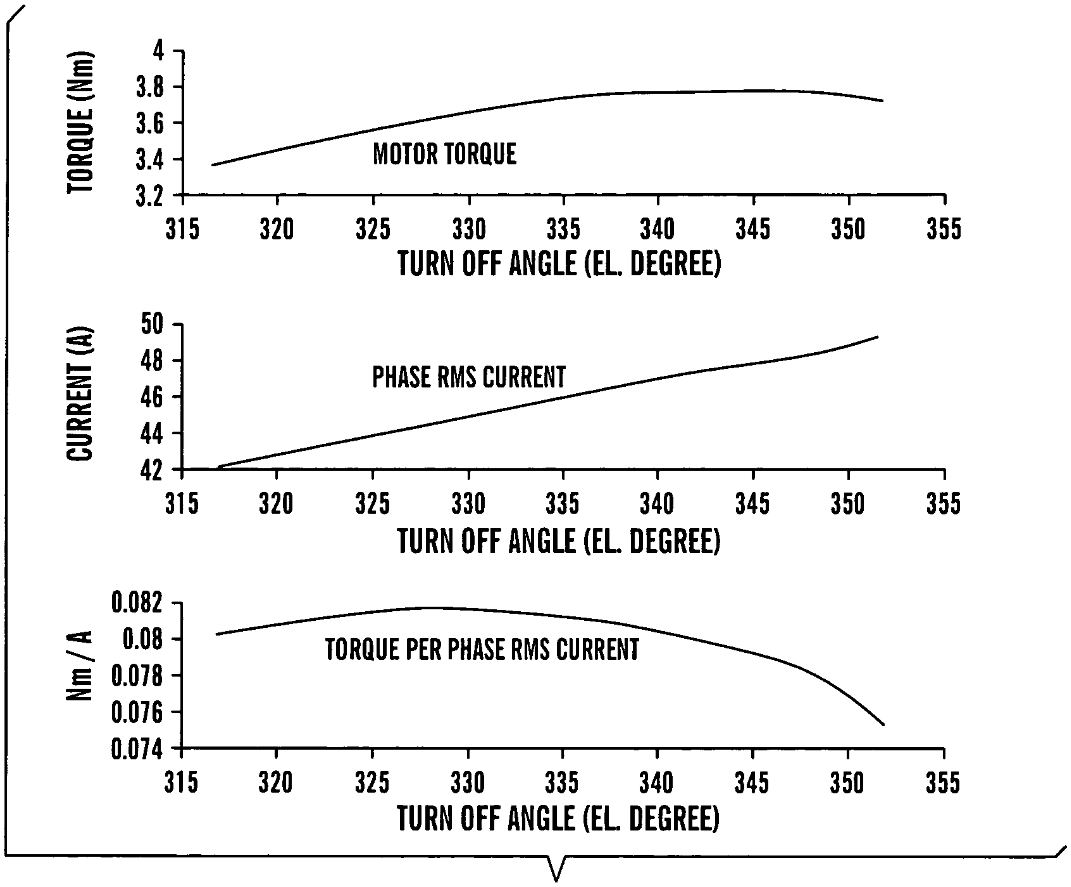
TORQUE (Nm)
4
3.8
3.6
3.4
3.2
MOTOR TORQUE
315
320
325
330
335
340
345
350
355
TURN OFF ANGLE (EL. DEGREE)
CURRENT (A)
50
48
46
44
42
PHASE RMS CURRENT
315
320
325
330
335
340
345
350
355
TURN OFF ANGLE (EL. DEGREE)
Nm / A
0.082
0.08
0.078
0.076
0.074
TORQUE PER PHASE RMS CURRENT
315
320
325
330
335
340
345
350
355
TURN OFF ANGLE (EL. DEGREE)

FIG. 4

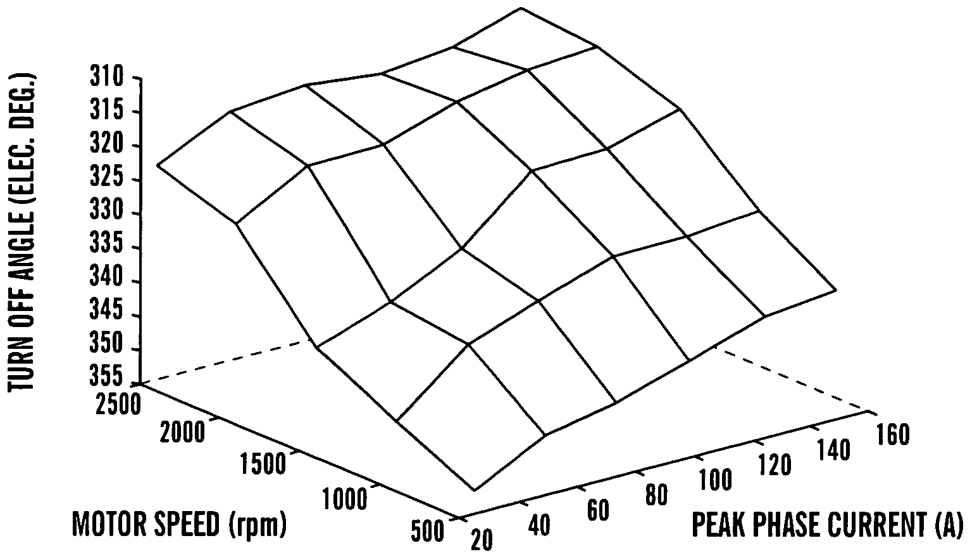
TURN OFF ANGLE (ELEC. DEG.)
310
315
320
325
330
335
340
345
350
355
2500
2000
1500
1000
500
MOTOR SPEED (rpm)
20
40
60
80
100
120
140
160
PEAK PHASE CURRENT (A)

FIG. 5

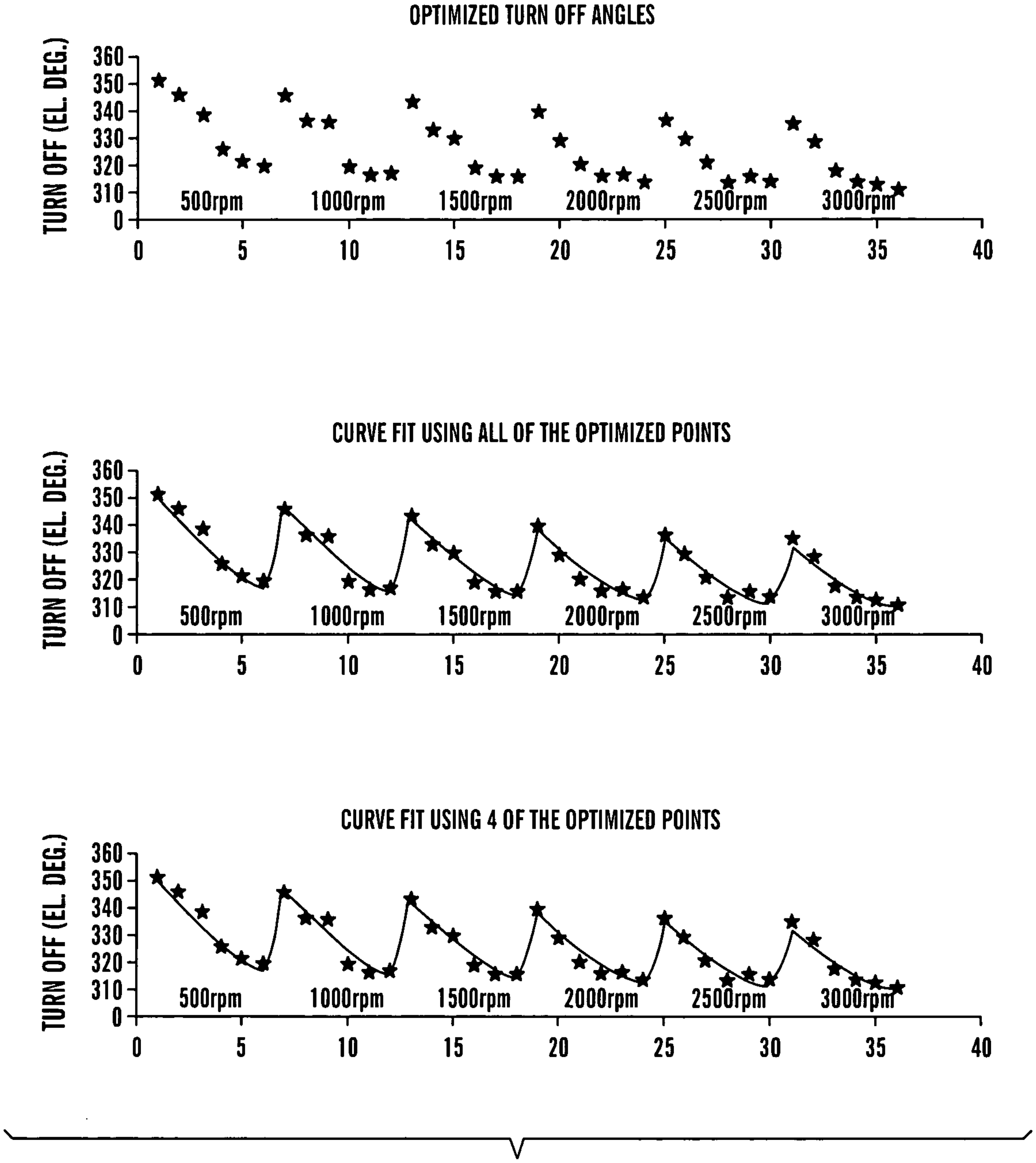
OPTIMIZED TURN OFF ANGLES
TURN OFF (EL. DEG.)
360
350
340
330
320
310
0
500rpm
1000rpm
1500rpm
2000rpm
2500rpm
3000rpm
0
5
10
15
20
25
30
35
40
CURVE FIT USING ALL OF THE OPTIMIZED POINTS
TURN OFF (EL. DEG.)
360
350
340
330
320
310
0
500rpm
1000rpm
1500rpm
2000rpm
2500rpm
3000rpm
0
5
10
15
20
25
30
35
40
CURVE FIT USING 4 OF THE OPTIMIZED POINTS
TURN OFF (EL. DEG.)
360
350
340
330
320
310
0
500rpm
1000rpm
1500rpm
2000rpm
2500rpm
3000rpm
0
5
10
15
20
25
30
35
40

FIG. 6

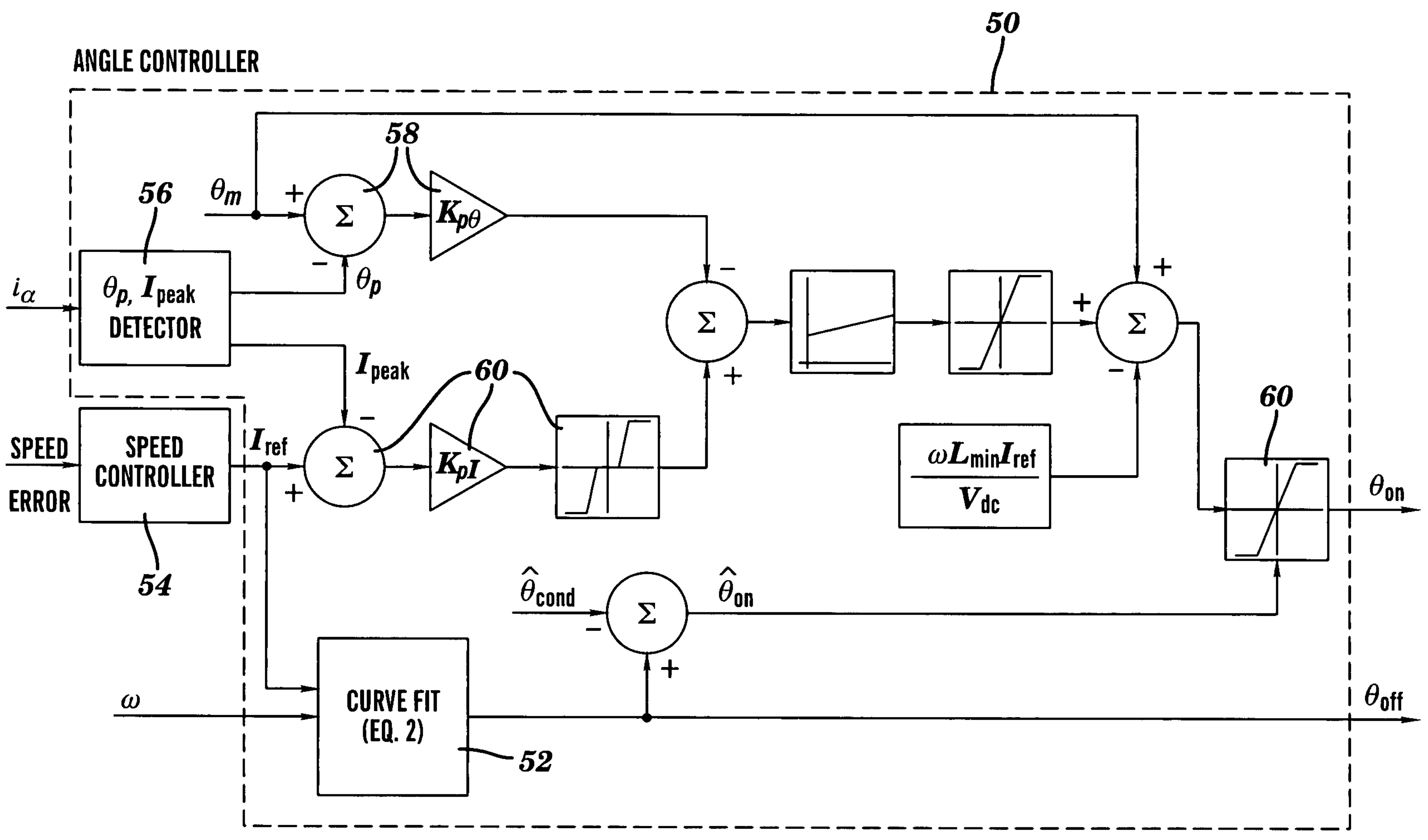
50
ANGLE CONTROLLER
56
58
θ_m
+
−
Σ
$K_{p\theta}$
i_α
θ_p, I_{peak}
DETECTOR
θ_p
I_{peak}
60
−
+
SPEED
ERROR
SPEED
CONTROLLER
54
I_{ref}
K_{pI}
$\frac{\omega L_{min} I_{ref}}{V_{dc}}$
θ_{on}
$\hat{\theta}_{cond}$
$\hat{\theta}_{on}$
ω
CURVE FIT
(EQ. 2)
52
θ_{off}

FIG. 7

TABLE 1: THE SPECIFICATIONS FOR THE EXPERIMENTAL SRM.

QUANTITY	VALUE	UNITS
RATED POWER	1000	W
BASE SPEED	1500	rpm
MAXIMUM SPEED	3,000	rpm
Dc VOLTAGE	12	V
NUMBER OF ROTOR POLES	12	
NUMBER OF STATOR POLES	16	
NUMBER OF PHASES	4	
ALIGNED PHASE INDUCTANCE	0.228	mH
UNALIGNED PHASE INDUCTANCE	0.0226	mH
θ_g	142	° (ELECTRICAL)
θ_m	218	° (ELECTRICAL)

TABLE 2: THE PARAMETERS FOR THE CONTROLLERS OF FIGS. 6.

QUANTITY	VALUE	UNITS
$K_{p\theta}$	0.033	
K_{pI}	1.899	° / A (ELECTRICAL)
θ_{cond}	178	° (ELECTRICAL)
κ_1	-8.106e-5	°s / A (ELECTRICAL)
κ_2	-1.397e-2	°s (ELECTRICAL)
κ_3	-9.278e-1	° / $\sqrt{A}$ (ELECTRICAL)
κ_4	3.556e2	° (ELECTRICAL)
PROPORTIONAL GAIN	0	
INTEGRAL GAIN	78	s^{-1}

FIG. 8

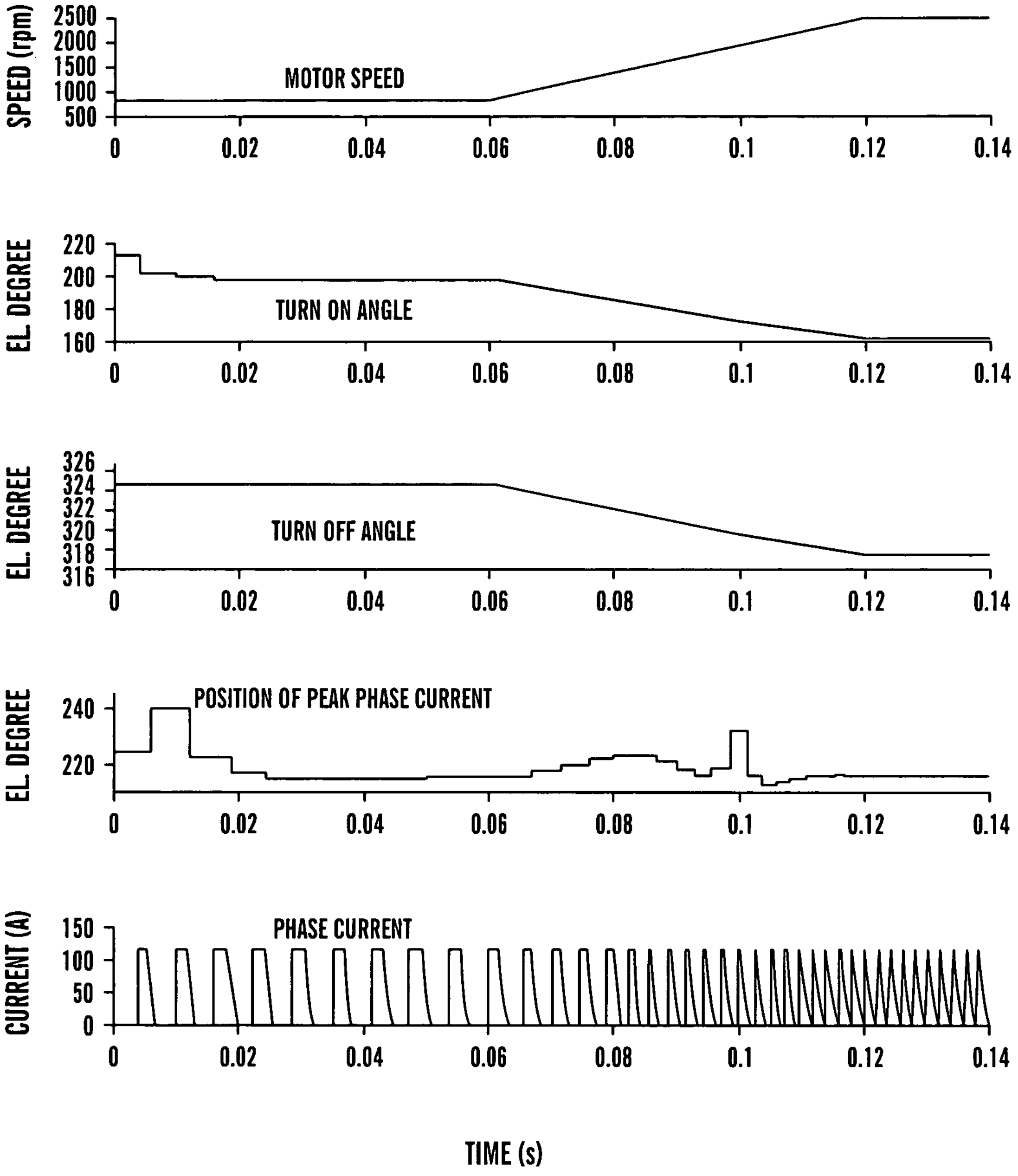
SPEED (rpm)
2500
2000
1500
1000
500
MOTOR SPEED
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
EL. DEGREE
220
200
180
160
TURN ON ANGLE
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
EL. DEGREE
326
324
322
320
318
316
TURN OFF ANGLE
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
EL. DEGREE
240
220
POSITION OF PEAK PHASE CURRENT
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
CURRENT (A)
150
100
50
0
PHASE CURRENT
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
TIME (s)

FIG. 9

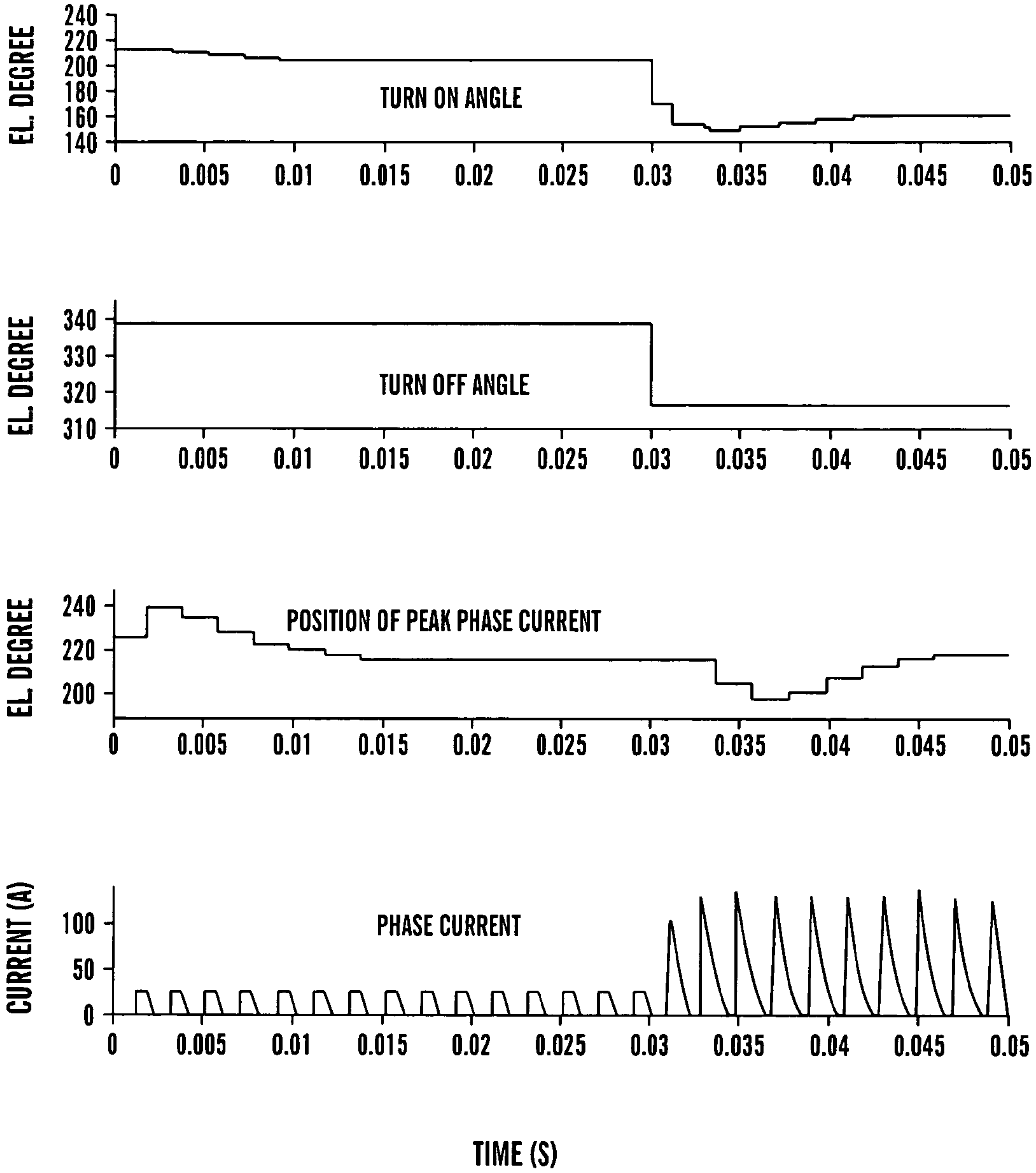
EL. DEGREE
240
220
200
180
160
140
TURN ON ANGLE
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
EL. DEGREE
340
330
320
310
TURN OFF ANGLE
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
EL. DEGREE
240
220
200
POSITION OF PEAK PHASE CURRENT
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
CURRENT (A)
100
50
0
PHASE CURRENT
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
TIME (S)

FIG. 10

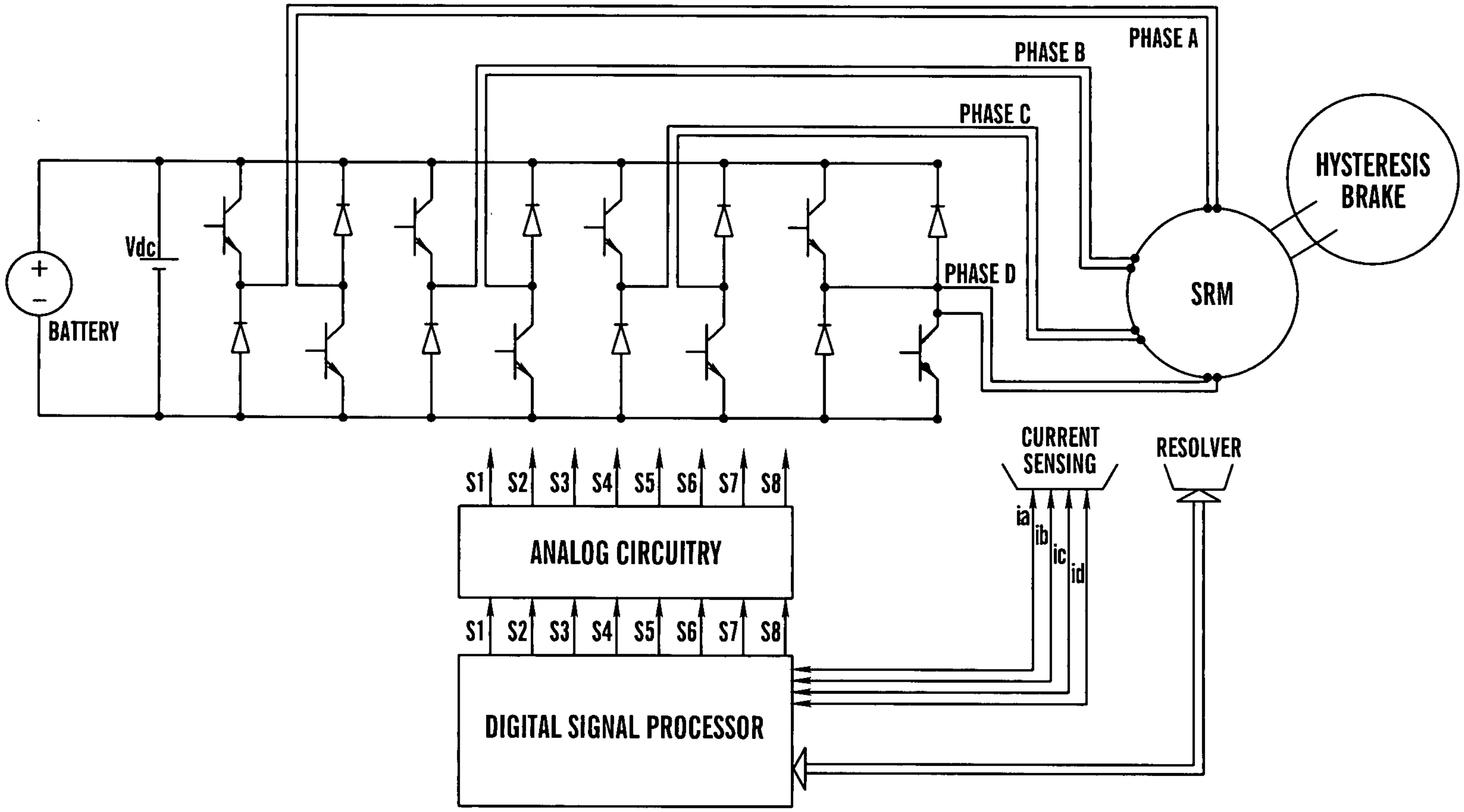
PHASE A
PHASE B
PHASE C
PHASE D
HYSTERESIS BRAKE
SRM
Vdc
BATTERY
+
−
S1
S2
S3
S4
S5
S6
S7
S8
ANALOG CIRCUITRY
S1
S2
S3
S4
S5
S6
S7
S8
DIGITAL SIGNAL PROCESSOR
CURRENT SENSING
ia
ib
ic
id
RESOLVER

FIG. 11

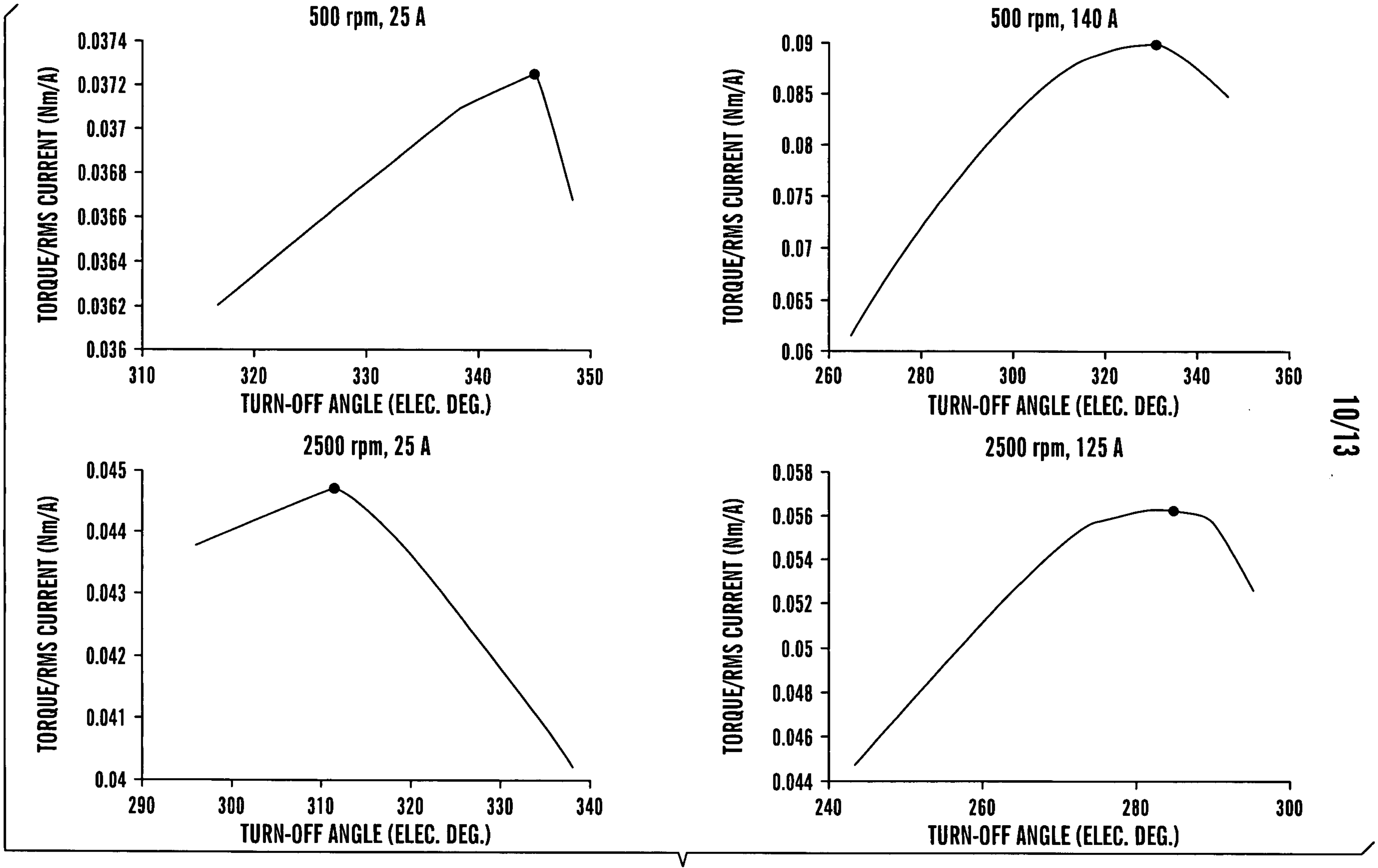
500 rpm, 25 A
TORQUE/RMS CURRENT (Nm/A)
0.0374
0.0372
0.037
0.0368
0.0366
0.0364
0.0362
0.036
310
320
330
340
350
TURN-OFF ANGLE (ELEC. DEG.)
500 rpm, 140 A
TORQUE/RMS CURRENT (Nm/A)
0.09
0.085
0.08
0.075
0.07
0.065
0.06
260
280
300
320
340
360
TURN-OFF ANGLE (ELEC. DEG.)
2500 rpm, 25 A
TORQUE/RMS CURRENT (Nm/A)
0.045
0.044
0.043
0.042
0.041
0.04
290
300
310
320
330
340
TURN-OFF ANGLE (ELEC. DEG.)
2500 rpm, 125 A
TORQUE/RMS CURRENT (Nm/A)
0.058
0.056
0.054
0.052
0.05
0.048
0.046
0.044
240
260
280
300
TURN-OFF ANGLE (ELEC. DEG.)

FIG. 12

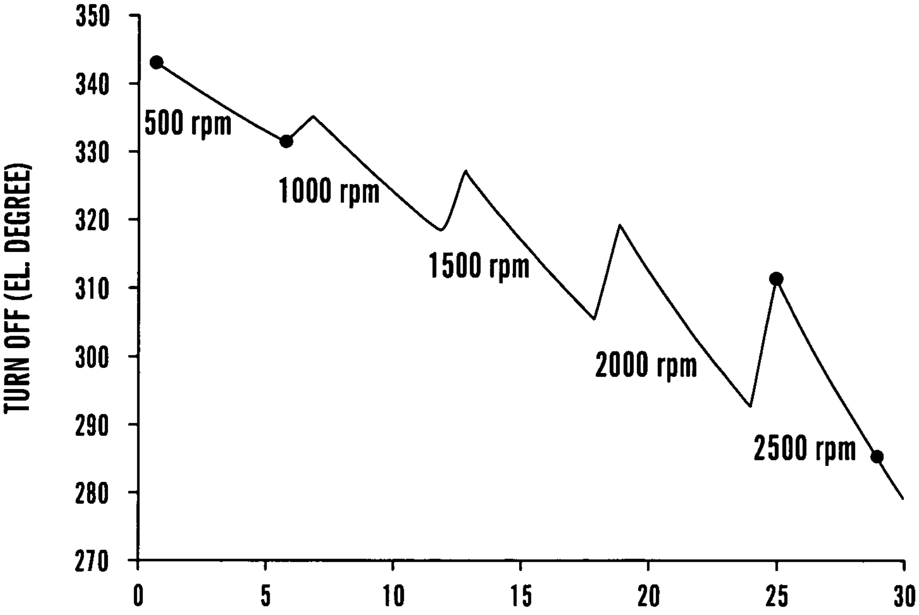
350
340
330
320
310
300
290
280
270
TURN OFF (EL. DEGREE)
0
5
10
15
20
25
30
500 rpm
1000 rpm
1500 rpm
2000 rpm
2500 rpm

FIG. 13

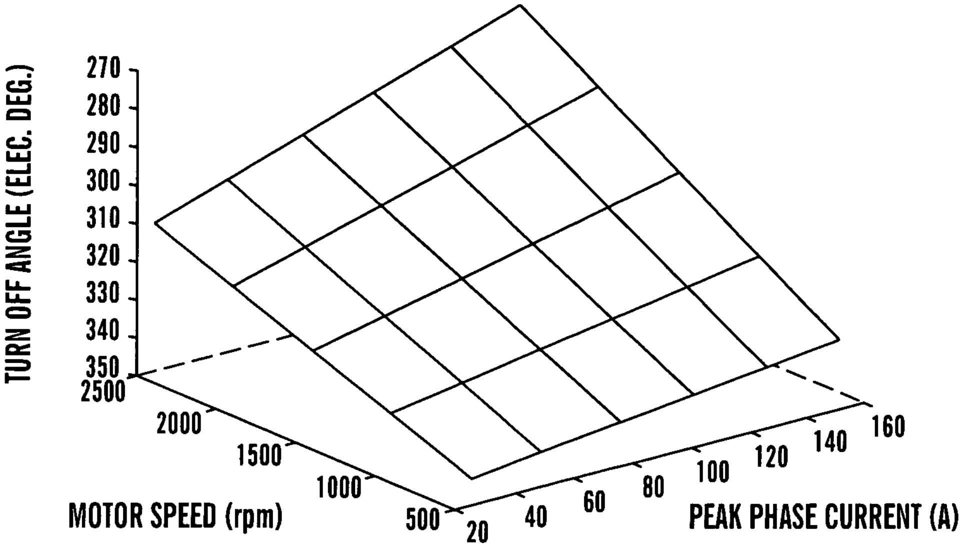
270
280
290
300
310
320
330
340
350
TURN OFF ANGLE (ELEC. DEG.)
2500
2000
1500
1000
500
MOTOR SPEED (rpm)
20
40
60
80
100
120
140
160
PEAK PHASE CURRENT (A)

FIG. 14

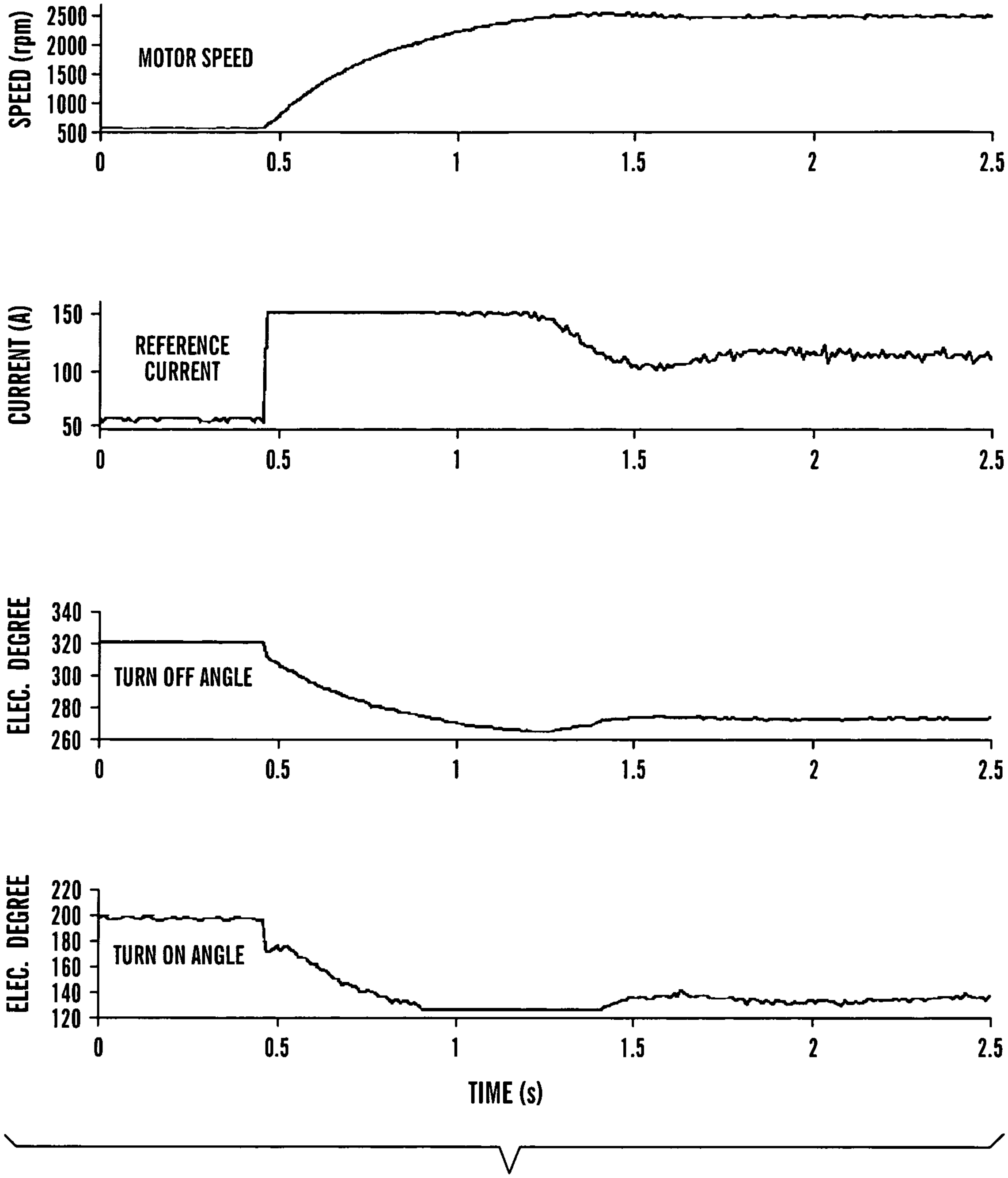
SPEED (rpm)
2500
2000
1500
1000
500
MOTOR SPEED
0
0.5
1
1.5
2
2.5
CURRENT (A)
150
100
50
REFERENCE CURRENT
0
0.5
1
1.5
2
2.5
ELEC. DEGREE
340
320
300
280
260
TURN OFF ANGLE
0
0.5
1
1.5
2
2.5
ELEC. DEGREE
220
200
180
160
140
120
TURN ON ANGLE
0
0.5
1
1.5
2
2.5
TIME (s)

FIG. 15

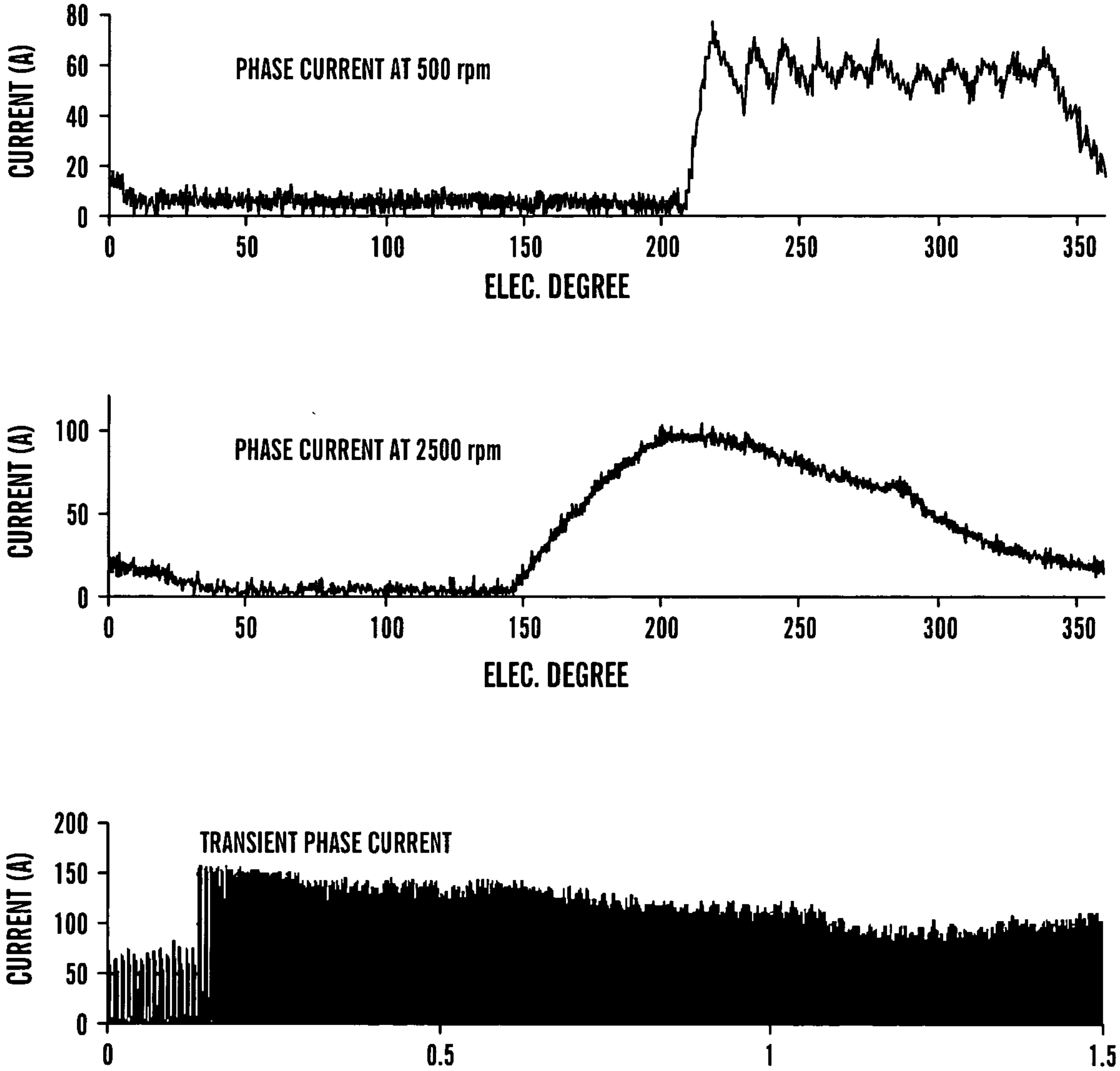
80
60
40
20
0
CURRENT (A)
PHASE CURRENT AT 500 rpm
0
50
100
150
200
250
300
350
ELEC. DEGREE
100
50
0
CURRENT (A)
PHASE CURRENT AT 2500 rpm
0
50
100
150
200
250
300
350
ELEC. DEGREE
200
150
100
50
0
CURRENT (A)
TRANSIENT PHASE CURRENT
0
0.5
1
1.5

FIG. 16